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Analyzing power A_y for ω meson production in proton–proton collisions

COSY-TOF Collaboration

M. Abdel-Bary [c], K.-Th. Brinkmann [a], H. Clement [d], J. Dietrich [a], E. Doroshkevich [d], S. Dshemuchadse [a], K. Ehrhardt [d], A. Erhardt [d], W. Eyrich [b], H. Freiesleben [a], A. Gillitzer [c], J. Gottwald [a], R. Jäkel [a], L. Karsch [a], K. Kilian [c], E. Kuhlmann [a], H.P. Morsch [c,e], C. Pizzolotto [b], S. Reimann [a], J. Ritman [c], E. Roderburg [c], W. Schroeder [b], M. Schulte-Wissermann [a], T. Sefzick [c], G.Y. Sun [a], A. Teufel [b], W. Ullrich [a,*], R. Wenzel [a], P. Wintz [c], P. Wüstner [c], P. Zupranski [e]

[a] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany*
[b] *Physikalisches Institut, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany*
[c] *Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[d] *Physikalisches Institut, Universität Tübingen, D-72076 Tübingen, Germany*
[e] *Soltan Institute for Nuclear Studies, 05-400 Swierk/Otwock, Poland*

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Abstract

We report on a determination of the analyzing power A_y in the $\vec{p}p \to pp\omega$ reaction studied with the TOF spectrometer located at the COSY-accelerator (Forschungszentrum Jülich, Germany). This spectrometer is very well suited for polarization measurements due to its rotational symmetry and full coverage of the azimuthal angle. For a beam momentum of $p = 3065\ \text{MeV}/c$ corresponding to an excess energy of $\epsilon = 129\ \text{MeV}$ A_y is found to be compatible with zero.
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1. Introduction

The reaction $pp \to pp\omega$ has been studied near threshold and at moderate excess energies up to $\epsilon = 320\ \text{MeV}$ ($\epsilon = \sqrt{s} - \sqrt{s_0}$, $\sqrt{s_0}$: threshold energy) by means of electronic detector systems since the late 1990s [1–4]. Bubble chamber data exist at excess energies of 400–1800 MeV [5]. The energy dependence of the measured total cross sections is reproduced well by several theoretical models describing the ω production via one pion exchange [6], nucleon resonances [7] or nucleonic and mesonic currents [8]. In order to discriminate between the different theoretical approaches and to improve the understanding of the reaction dynamics involved, angular distributions have been measured as well [2–4,9]. A further step, which may help to clarify the reaction mechanism, is the measurement of polarization observables, since they are in particular sensitive to the contributing partial waves. So far no data exists for polarization observables in this channel. As a first step the analyzing power A_y is determined in an experiment utilizing a polarized proton beam incident on an unpolarized proton target ($\vec{p}p \to pp\omega$) which gives additional constraints for a partial wave analysis. This may help to refine the theoretical models [6–8].

2. Detector setup

The Time-Of-Flight spectrometer TOF [10] is an external experiment at the COoler SYnchrotron COSY (Jülich). The

* Corresponding author.
E-mail address: w.ullrich@physik.tu-dresden.de (W. Ullrich).

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proton beam hits a 4 mm thick liquid hydrogen target and the emerging reaction products traverse a layered time-of-flight start and tracking detector. After a flight path of ≈ 3 m in vacuum the ejectiles are detected in the highly granulated stop components of the spectrometer. From time and position measurements the velocity vectors of all charged particles are determined with a time-of-flight resolution of better than $\sigma_{\mathrm{TOF}} = 300$ ps and angular track-resolution of better than $\sigma_{\sphericalangle} = 0.3°$. Due to the low mass area density of all detector components, the influence of small angle scattering and energy loss is almost negligible for particles with $\beta > 0.5$. Only particles with these velocities are produced in the reaction under study. Unlike magnetic spectrometers, which provide particle identification often at the cost of limited acceptance, the TOF detector stands out for its large geometric acceptance ($1° < \theta_{\mathrm{lab}} < 60°$, $0° < \phi < 360°$) and a detector efficiency $> 95\%$ for the detection of charged particles. This allows the unambiguous and simultaneous identification of different reaction channels (e.g., $pp \to pp, d\pi^+, pK^+\Lambda, pK^+\Sigma^0, pp\omega$) by examining their event topology.

3. Beam polarization measurement

The TOF detector is very well suited for polarization experiments. It not only covers the azimuthal angular range (ϕ) completely, but also the detector is symmetric around the beam axis. The data presented in this Letter was obtained using a transversally polarized proton beam at a beam momentum of $p_{\mathrm{beam}} = 3065$ MeV/c. The polarization was flipped between each operation cycle of COSY where each cycle took about 120 s. This method minimizes possible systematic effects. The total counts of elastically scattered events for both spin orientations are equal with an uncertainty of 0.3%, that was also confirmed by the independently measured numbers of beam protons by means of a beam hodoscope. Therefore the integrated luminosities for the two data sets can be treated as equal.

A precise knowledge of the beam polarization "on target" is important in order to quantitatively extract polarization observables of any reaction channel. The appropriate tool at TOF is the analysis of the proton–proton elastic scattering, for which more than 7×10^6 events were found in total. Using this large data basis, the polarization was determined in a two step process. Firstly, the asymmetry $\alpha(\theta^*)$ was determined.

For a polarization along the y-axis,[1] P_y, the differential cross section $\sigma(\theta^*, \phi)$ is given by $\sigma(\theta^*, \phi) = \sigma_0(\theta^*)(1 + P_y A_y(\theta^*, \phi))$ where $\sigma_0(\theta^*)$ is the differential cross section for an unpolarized beam and $A_y(\theta^*, \phi)$ is the analyzing power. Since the dependence of A_y on the azimuthal angle is given by a cosine function of ϕ we denote the amplitude of this cosine function by $A_y(\theta^*)$ or in short, A_y. Then the asymmetry

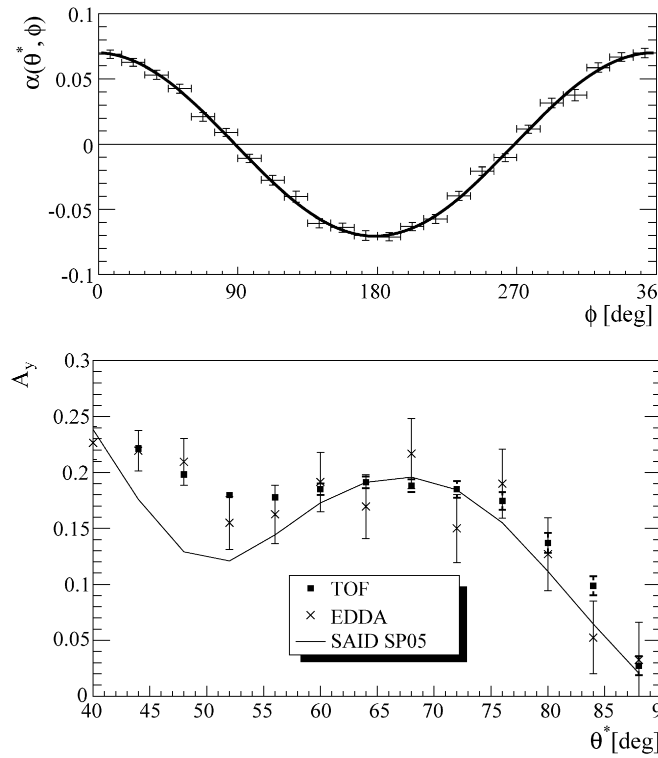

Fig. 1. Upper frame: Measured asymmetry $\alpha(\theta^*, \phi)$ for $42° < \theta^* < 46°$; statistical uncertainties are given. The horizontal bars reflect the width of the ϕ intervals. Lower frame: Analyzing powers A_y versus θ^* from SAID [12] together with data from EDDA and TOF. The measured asymmetries from TOF (with statistical uncertainties) has been scaled to the EDDA data, for which total uncertainties are given.

$\alpha(\theta^*, \phi)$ can be expressed as

$$\alpha(\theta^*, \phi) = \bar{P}_y A_y \cdot \cos\phi = \frac{\sigma_\uparrow(\theta^*, \phi) - \sigma_\downarrow(\theta^*, \phi)}{\sigma_\uparrow(\theta^*, \phi) + \sigma_\downarrow(\theta^*, \phi)}, \tag{1}$$

where $\bar{P}_y$ is the average of the absolute value of the beam polarization for both orientations, 'up' and 'down', and $\sigma_{\uparrow,\downarrow}(\theta^*, \phi)$ denotes the differential cross section for the two orientations. With the number of particles $N_{\uparrow,\downarrow} = \sigma_{\uparrow,\downarrow} \cdot \mathcal{L}_{\uparrow,\downarrow} \cdot \epsilon$ observed in a small solid angle interval $[\theta_1^*\phi_1, \theta_2^*\phi_2]$, the asymmetry for this solid angle interval is obtained as:

$$\alpha = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}, \tag{2}$$

since the integrated luminosities as well as the efficiency ϵ that is constant over the small angular intervals for the pp elastic and ω channel, cancel. Technically, the collected elastic scattering events were grouped into small bins in polar and azimuthal angles of the direction of the scattered protons. For both spin orientations the number of registered protons was determined for each bin and from these two numbers the asymmetry was calculated according to Eq. (2). For each θ^* interval a cosine-shaped distribution resulted. The amplitude of the corresponding cosine fit yields the asymmetry $\alpha(\theta^*)$ for the respective θ^* interval. An example is shown in Fig. 1 in the upper frame.

In the second step, the beam polarization $\bar{P}_y$ was determined by scaling the obtained asymmetry values with one common factor to known data for the analyzing power A_y. The beam

[1] A right-handed coordinate system is used where z is defined by the beam axis and y is the vertical axis, aligned with the orientation of beam polarization for 'spin up'. θ and ϕ are the polar and azimuthal angle in the corresponding spherical coordinate system, where asterisks indicate center-of-mass angles.

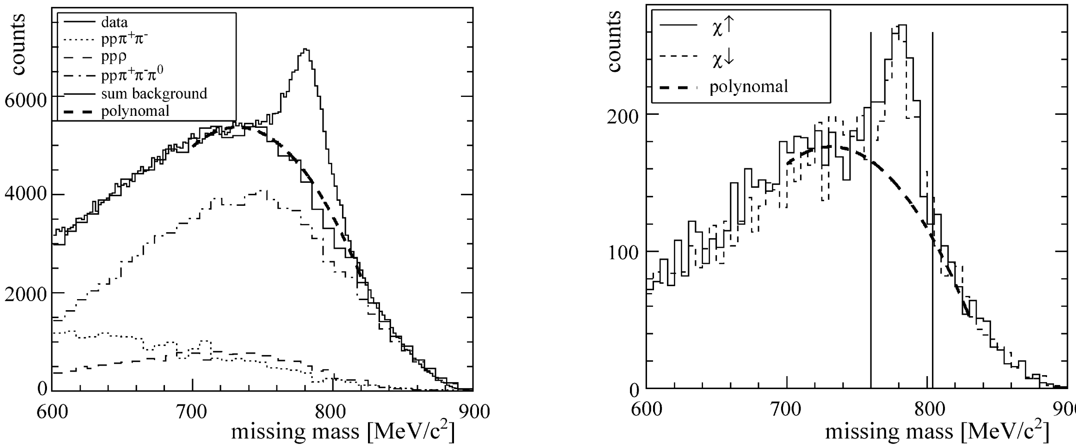

Fig. 2. Left: Total missing mass spectrum with Monte Carlo simulations of relevant background channels and a 2nd order polynomial that is used to describe the background under the ω signal. Right: Missing-mass spectra for the interval $0.6 < \cos\theta^*_\omega < 0.8$ and $-22.5° < \phi_\omega < 22.5°$ for both spin orientations. The 2nd order polynomial describes the average background. The vertical lines indicate the limits chosen for the integration.

polarization then is simply the reciprocal value of this factor. The result is shown in the lower frame of Fig. 1 together with data from EDDA [11] and the latest SAID solution SP05 [12], that includes the EDDA data. Here the EDDA data is an interpolation of two available data sets at 3045 MeV$/c$ and 3075 MeV$/c$ that are equal within uncertainties. The partial wave analysis SAID apparently disagrees with the TOF and EDDA data at $\theta^* \leqslant 50°$. We used the measured data from EDDA for the determination of the polarization and obtained a value of $\bar{P}_y = 0.32 \pm 0.03$, where the accuracy is mainly limited by the uncertainty of the EDDA data. An analysis of the elastic scattering in intervals of two hours length during the whole experiment has shown COSY-related variations of up to ± 0.07 in the beam polarization over the beam time and of about ± 0.02 during a spill. The results shown in Fig. 1 demonstrate the perfect azimuthal symmetry of the COSY-TOF spectrometer and its excellent capability to measure high precision polarization data.

4. Results for $\vec{p}p \to pp\omega$

At TOF, the reaction $pp \to pp\omega$ is preselected via the main decay channel of the ω meson ($\omega \to \pi^+\pi^-\pi^0$, $\mathcal{BR} \approx 89.1\%$) which leads to four charged particles measured in the detector and one unobserved neutral pion. The outgoing protons and the charged pions, due to their large mass difference, are clearly separated in a velocity vs. polar angle representation [9]. This separation is used to identify protons and to calculate their four-momenta using the measured velocity vectors. The main sources of background are the non-resonant and resonant two-pion production channels. Their contribution was reduced by a constraint on the acoplanarity of the pion candidates with the reconstructed meson since for an ω decaying into three pions the plane defined by the two observed pions does in general not contain the direction of the meson (cut on acoplanarity $\alpha > 5°$, for details see [3,9]). The analysis only considered events where the sum of momenta of the two protons points into the backward hemisphere of the CMS, since in these cases the protons are slower in the laboratory frame and the momentum resolution achieved is therefore significantly better. Hence, the determination of $A_y(\theta^*_\omega)$ is restricted to $0 < \cos\theta^*_\omega < 1$.

Using the four-momenta of the two protons the missing mass was calculated. The resulting spectrum is shown in the left frame of Fig. 2, where a clear ω signal is visible above a smooth and structureless background. This background could be very well reproduced by Monte Carlo simulations of the most important channels $pp \to pp\pi^+\pi^-$, $pp \to pp\rho$, $pp \to pp\pi^+\pi^-\pi^0$, which were analyzed in the very same way as the real data. Since the cross sections of the different background reactions are not known, their contribution was adjusted to reproduce the experimental background. An alternative method applied is a simultaneous fit to the data with a Voigt function for the ω signal and a 2nd order polynomial for the background under the signal. The background determined by this procedure is in very good agreement with the background determined by the Monte Carlo simulations, as demonstrated in the left frame of Fig. 2. Hence the simultaneous fit of a Voigt function and a 2nd order polynomial is both an effective and appropriate means to determine the number of events to be attributed to the ω-channel, and is used in the further analysis studies with different cuts gave a systematical uncertainty of 7% for the determination of the number of events in the ω peak. In total 40 000 ω events were found.

For the determination of the analyzing power A_y, missing mass spectra were created for five bins in polar and eight in azimuthal angle of the ω in the CMS and for two spin orientations of the proton beam (altogether 80 spectra). Examples of the missing mass distributions are shown in the right frame of Fig. 2 for the interval $0.6 < \cos\theta^*_\omega < 0.8$ and $-22.5° < \phi_\omega < 22.5°$. To further reduce the systematic uncertainty for the determination of the asymmetry of the ω signal an average background for each pair of spectra was determined. The background was found to not depend on the orientation of the polarization as shown in the right panel of Fig. 2. From the counts in the ω peak the asymmetry was determined using Eq. (2). Sidebands below and above the ω signal

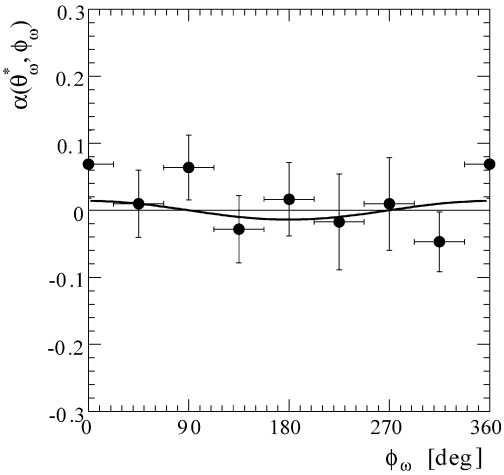

Fig. 3. Asymmetry $\alpha(\theta^*_\omega, \phi_\omega)$ for one interval in polar angle ($0.6 < \cos\theta^*_\omega < 0.8$). One data point is inserted twice at 0° and 360°. The horizontal bars reflect the width chosen for the ϕ_ω-intervals.

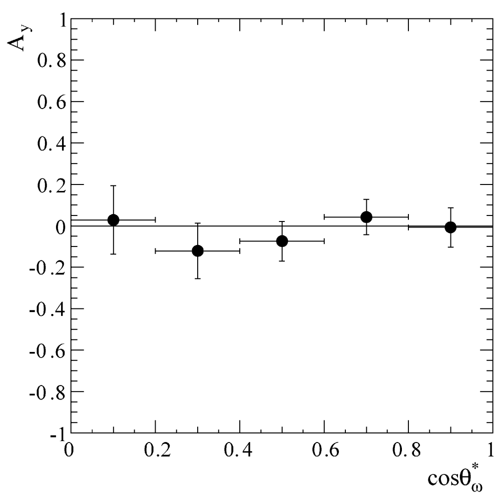

Fig. 4. Analyzing power for the $\vec{p}p \to pp\omega$ reaction. The horizontal bars reflect the width chosen for the $\cos\theta^*_\omega$ intervals

showed no asymmetry of the background for any of the angular bins.

As an example, the result for the asymmetry $\alpha(\theta^*_\omega, \phi_\omega)$ in the polar angle interval $0.6 < \cos\theta^*_\omega < 0.8$ is shown as a function of the azimuthal angle in Fig. 3. The numerical value of the asymmetry $\alpha(\theta^*_\omega)$ was obtained from the amplitude of a $\cos\phi_\omega$ fit to the data. Applying the same procedure to all five bins of the polar angle, and taking into account the beam polarization, the analyzing powers A_y were calculated. The uncertainties of the fits were taken to be the uncertainties of the analyzing power for the respective polar angle interval (see Table 1). The result is shown in Fig. 4. All measured values agree with zero within the quoted uncertainty. Different cosine fits with different numbers of free parameters as well as a fit to the so-called "super ratio" [13], a symmetrization where the geometric means from the count rates measured for opposite directions of the ω direction with opposite spin orientations of the incident proton beam are used in Eq. (2), yielded almost identical results.

Table 1
Analyzing power A_y. The errors quoted denote the uncertainties as described in the text. There is an additional systematic error of 10% due to the uncertainty of the beam polarization

$\cos\theta^*_\omega$	A_y
0.0–0.2	0.03 ± 0.16
0.2–0.4	-0.11 ± 0.13
0.4–0.6	-0.07 ± 0.11
0.6–0.8	0.04 ± 0.09
0.8–1.0	-0.02 ± 0.12

Table 2
List of the lowest partial waves. The notation is defined in the text

Type	$({}^{2S+1}L_J)_i \to ({}^{2S+1}L_J)_f l_\omega$
Ss	${}^3\mathrm{P}_1 \to {}^1\mathrm{S}_0\ s$
Sp	${}^1\mathrm{S}_0 \to {}^1\mathrm{S}_0\ p$
	${}^1\mathrm{D}_2 \to {}^1\mathrm{S}_0\ p$
Ps	${}^1\mathrm{S}_0 \to {}^3\mathrm{P}_1\ s$
	${}^1\mathrm{D}_2 \to {}^3\mathrm{P}_1\ s$
	${}^1\mathrm{D}_2 \to {}^3\mathrm{P}_2\ s$

5. Discussion

While the description of the production of the light pseudoscalar mesons is quite advanced [14,15], only recently effort has been devoted to the description of polarization observables for vector mesons [15–17]. The data presented here are the first on this topic which hopefully will trigger further theoretical work. In the following we will discuss our result based on fundamental symmetries such as the Pauli principle, angular momentum and parity conservation. The notation $({}^{2S+1}L_J)_i \to ({}^{2S+1}L_J)_f l_\omega$ follows the convention of [14]. The angular momentum of the proton–proton system is denoted by L, the spin by S and the total angular momentum by J. Subscripts i and f signify initial and final state, respectively, l_ω denotes the angular momentum of the ω meson relative to the proton–proton system.

At threshold the exit channel is in a ${}^1\mathrm{S}_0$ s state, i.e., no angular momenta are present except the intrinsic spin 1 of the ω meson. Thus the entrance channel must be in a ${}^3\mathrm{P}_1$ state. As long as only this partial wave contributes, A_y must vanish. However, the results of [9] show the onset of higher partial waves contributing to the reaction at an excess energy of $\epsilon = 93$ MeV. Further, in [3] a strong anisotropy of the angular distribution of the ω meson in the overall CMS frame at $\epsilon = 173$ MeV was reported. Thus, higher partial waves must be present at the excess energy studied here ($\epsilon = 129$ MeV) and a vanishing analyzing power is therefore somewhat unexpected.

Taking into account higher angular momenta in the exit channel one can construct the lowest six partial waves which can contribute; they are listed in Table 2. Here we only consider one p-wave in the exit channel, since the excess energy is still quite low and a proton–proton P-wave along with an ω p-wave is not likely to occur.

In general, for $A_y \neq 0$ we need at least two interfering partial waves with one having $S = 1$ in the entrance channel. Considering the partial waves of Table 2 this can be fulfilled by the first and second and by the first and third partial wave. The partial waves of type Ps cannot contribute since they have $S = 1$ in the exit channel in contrast to the partial waves of type Ss and Sp that have $S = 0$ in the exit channel. The Ps partial waves would contribute if they could interfere with an even higher partial wave, e.g., Pp, with $S = 1$ in the entrance and exit channel. Only considering the partial waves in Table 2, the analyzing power follows [15]

$$A_y \propto \mathrm{Im}\bigl(f_1^*(f_2 - 1/3 f_3)\bigr) k \sin\theta_\omega^* \cos\phi_\omega, \tag{3}$$

here k denotes the absolute value of the ω momentum in the CMS and f_ν denote the amplitude for the νth partial wave listed in the order given in Table 2. That means our result $f_1^*(f_2 - 1/3 f_3) \approx 0$ indicates $f_1 \approx 0$ or $f_2 \approx 3 f_3$ or $f_2 \approx f_3 \approx 0$ or $f_1^* \perp f_2$ and $f_1^* \perp f_3$. This finding relates the amplitudes f_1, f_2, f_3 in a definite manner. The amplitudes, however, need to be calculated along the various models on meson production [6–8]. Only then their capability of describing the data presented can be assessed and information on the reaction mechanism involved can be obtained.

6. Conclusion

A first measurement of the analyzing power A_y for ω production in proton–proton collisions was performed at COSY with the TOF spectrometer. A_y was found to be zero at an excess energy of $\epsilon = 129$ MeV. Obviously, this result does not rule out a non-vanishing analyzing power below or above this excess energy. It is challenging to compare theoretical predictions of analyzing powers at different energies with future data which can be obtained with the TOF spectrometer up to excess energies of $\epsilon = 200$ MeV. Its capability to carry out high quality polarization measurements at COSY was demonstrated by the determination of the beam polarization, the uncertainty of which is completely governed by the uncertainties of the reference data.

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